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Solar Proton Events During the Past Three Solar Cycles

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More than 200 solar proton events with a flux of over 10 particles $(cm^2\text{-}s\text{-}sr)^{-1}$ above 10 MeV have been recorded at the Earth since 1955; at least 15% of these events had protons with energies >450 MeV. Although the majority of solar proton events occur in the years around sunspot maximum, these events, including those with relativistic protons, also occur during sunspot minimum. Detector technology has evolved during the last three solar cycles so that a uniform data base does not exist. A count of the number of solar proton events above a specific flux level does not indicate a recognizable trend over the three solar cycles. However, an analysis of the particle fluence in "major" events indicates that the 19th solar cycle was the most energetic.

Introduction

THE fact that the sun can accelerate particles to high energies has been known for approximately 40 years. Solar particle events are referred to by a number of different names such as solar cosmic-ray events, solar proton events, solar electron events, polar cap absorption events, and ground-level events (GLE). To describe the solar particle events that have occurred during the past three solar cycles, it is necessary to understand several aspects of cosmic radiation such as the background radiation in space and solar particle propagation. Consequently, the first part of this paper will describe the galactic cosmic radiation and its solar modulation; the solar particle events during the last three solar cycles are discussed in later sections.

Charged Particle Background Radiation

There is a cosmic-radiation background present everywhere in space, the intensity being dependent upon the measurement location. Spacecraft outside the Earth's magnetosphere are constantly subjected to the background galactic cosmic radiation upon which the solar cosmic rays are episodically superposed. Spacecraft operating within the magnetosphere are subjected to this radiation; however, the shielding effects of the Earth's magnetic field reduce the total flux impinging upon the satellite by an amount that depends on the characteristics of the spacecraft orbit. Satellites in the polar regions will be subjected to the full intensity of galactic and solar particle flux; those in the equatorial regions will be subjected to lesser amounts depending on altitude. In addition to the galactic and solar cosmic-ray flux, spacecraft operating within the magnetosphere also encounter the trapped particle radiation.[1]

Galactic Cosmic Radiation

The galactic cosmic radiation (whose origin is still a matter of scientific debate) is composed of atomic nuclei that have been ionized and then accelerated to very high energies. The deposition of this energy can affect the material through which the cosmic ray passes. For small, state-of-the-art, solid-state electronic devices, the passage of cosmic-ray particles through the device can produce enough charge in the sensitive volume to change the state of a circuit element thereby causing a "soft error." Also, heavy cosmic-ray nuclei may cause displacements in the crystal structure and permanent damage. An examination of the effects of cosmic radiation on microelectronics is given by Adams et al.[2]

The energies of the cosmic radiation are normally expressed in units of GeV (10^9 eV). A 1-GeV proton can penetrate approximately 400 g-cm^{-2} of material, therefore shielding against galactic cosmic radiation in space is generally ineffective. The primary cosmic radiation observed at the Earth's orbit consists of approximately 83% protons, 13% alphas, 1% nuclei with atomic number $Z>2$, and 3% electrons. This composition extends over an energy range from approximately 10 MeV to $>10^{20}$ eV. A more detailed review oriented toward environmental specification is given by Smart and Shea.[3]

Solar Cycle of Galactic Modulation Cosmic Radiation

The Earth is located deep within the heliosphere (the domain controlled by solar emissions of plasma and magnetic field), which extends to perhaps several hundred times the sun-Earth distance. (The mean distance from the sun to the Earth is defined as an astronomical unit, or a.u.) Since cosmic-ray particles originate outside the heliosphere, they must "work" against the outflowing solar plasma and imbedded interplanetary magnetic field if they are to arrive in the inner solar system. Turbulence in the interplanetary medium is a function of solar activity; therefore, the cosmic-ray flux at the Earth is a function of the solar cycle. Since the solar activity increases the turbulence that the cosmic ray must "work" against, the minimum cosmic-ray flux is observed with the solar activity maximum. (There is an approximate seven-month lag between solar activity and cosmic-ray modulation that is interpreted as the time it takes the solar plasma to propagate out into the distant heliosphere.) Similarly, the cosmic rays perform a minimum amount of "work" against a quiet solar wind, so the cosmic-ray flux is maximum during solar minimum conditions. Models exist that will predict the cosmic-ray flux as a function of the cosmic-ray modulation parameter[4,5] described as a heliocentric electric field having a potential equal to the energy that arriving cosmic rays have lost. The cosmic-ray modulation parameter has not been successfully predicted, and proxies such as solar sunspot number predictions are used (see review of sunspot number predictions by Withbroe[6]). An example of using the sunspot number as a cosmic-ray intensity predictor is given by Adams et al.[2] and Adams.[7]

The solar cycle modulation of the galactic cosmic radiation observed at the Earth's surface by a neutron monitor is shown in Fig. 1. This figure illustrates that, within a small uncertainty, the cosmic-ray intensity has been approximately the same for each solar minimum for which we have measurements. The extent of the solar modulation on the cosmic-ray

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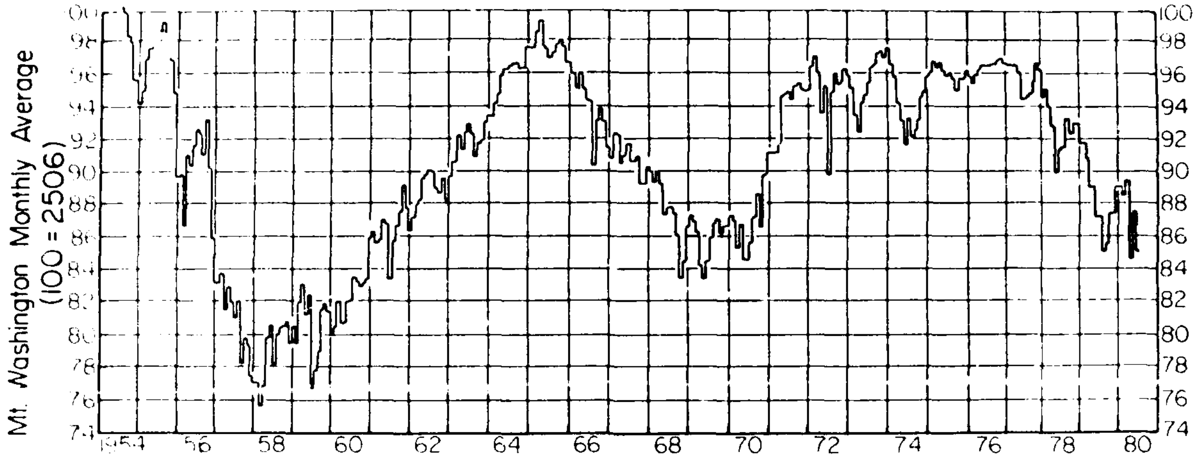

Fig. 1 Solar cycle modulation of cosmic rays.

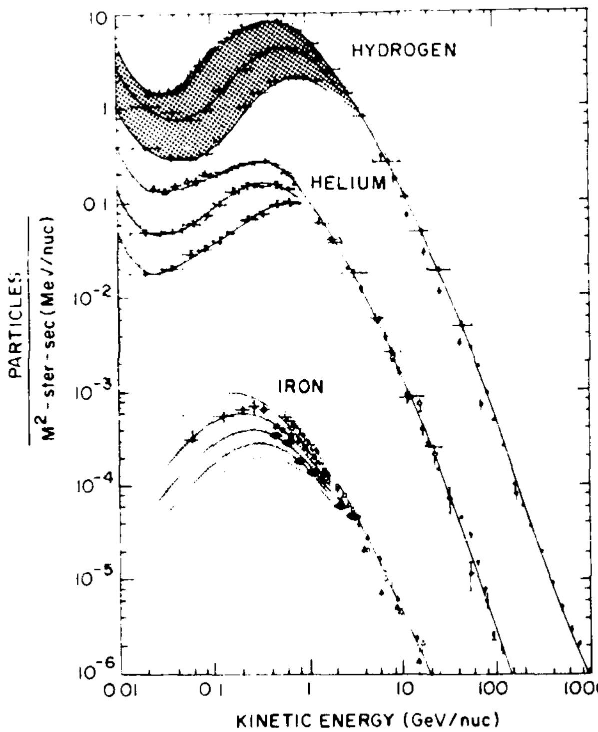

Fig. 2 Cosmic-ray differential energy spectrum for hydrogen, helium, and iron nuclei.

differential energy spectrum at 1 a.u. for hydrogen, helium, and iron nuclei is illustrated in Fig. 2 by the shaded area in the energy range from 0.01 to 10 GeV. The hydrogen flux has been multiplied by five so that the modulated spectra do not overlap. The very low energy particle-radiation background (energies of a few megaelectron volts per nucleon) is strongly influenced by solar activity and can easily vary by a factor of two during the 27-day solar rotation period. This portion of the charged-particle background is strongly associated with solar activity.

Anomalous Cosmic-Ray Component

During the decline of the 20th solar cycle, anomalies were found in the low-energy cosmic-ray background. This phenomenon was called the "anomalous cosmic-ray component" since the composition deviated from the "expected" cosmic-ray composition; specific elements such as helium and carbon were perhaps as much as 10 times "normal" abundances at energies near 10 MeV per nucleon. This "anomalous" cosmic-ray component, which extends from about 1–70 MeV per nucleon, is now explained as follows: Interstellar neutral gas that penetrates into the heliosphere toward the sun becomes ionized by the solar EUV emission. These newly created ions are then energized by poorly understood interplanetary acceleration processes. For a recent review of the anomalous cosmic-ray component, see McKibben.[8]

Solar Particles

Solar flare is the name given to the phenomenon observed in the solar chromosphere resulting from the sudden release of very large amounts of energy (see Svestka[9] for a suitable review). Solar flares produce electromagnetic emissions, accelerate electrons and ions, and, if conditions are favorable, inject these particles into space. Generally, characteristic electromagnetic emissions emanate from the site of energy release in a predictable sequence although, on occasion, certain emissions dominate. To a first-order approximation, the intensity of the radio and soft x-ray emissions observable at 1 a.u. is independent of the location of the flare on the sun. The exact process by which particles are accelerated in the solar active region is still debated, and a number of mechanisms are being studied. At present, the mechanisms can be broadly classified in two categories: impulsive mechanisms that may have several stages, and acceleration mechanisms based on the passage of shock waves through the corona.

At times, radio and x-ray emissions are detected without a corresponding optical emission, a phenomenon that usually occurs when the solar flare is behind the visible solar disk. At other times, types of emission normally expected with solar flare particle acceleration may be weak even for "significant" solar particle events.[10,11] Despite the popular belief that energetic solar particles are always associated with large solar flares, there have been measurements of $E > 50$ MeV protons at the Earth associated with a disappearing filament and without an accompanying flare.[12]

There is no unique indicator that a specific solar flare will generate a significant solar proton event. However, two relatively "good" indicators have an approximately 0.75 correlation: the "big flare syndrome" and the "U-shaped" radio peak-emission power spectrum. During the late 1960's and into the 1970's, Castelli and co-workers[13-15] noted an apparent "U-shaped" spectral signature in the peak power radio emission associated with solar proton events. However, in the 1980's a re-examination of the available data identified a number of exceptions to this generalization. The concept of the "big flare syndrome" was formalized by Kahler[16] who noted that the major solar emissions (x-rays, particles, and the various radio emanations) were usually associated with "significant" solar flares, and it was unclear whether or not any par-

ticular emission uniquely indicated solar particles. More recent work has reinforced this conclusion.

Solar Particle Propagation

To understand the solar particle data base acquired during the past three solar cycles, one must describe solar particle propagation. Energetic solar particles reach the orbit of the Earth within a few minutes if the particles have very high energies, or within hours for the lower-energy particles. Enhanced solar plasma usually propagates to the Earth within one or two days and causes aurora and geomagnetic disturbances whose magnitude depends on the interplanetary plasma and field characteristics when the plasma arrives and interacts with the Earth's magnetosphere. Figure 3 illustrates the relative time of arrival and duration of solar particle emission at the Earth.

Unlike solar electromagnetic radiation, both the onset time and maximum intensity of the solar particle flux depend on the heliolongitude of the flare with respect to the detection location in space. This directionality results because particles will move most easily along the interplanetary magnetic-field direction. The interplanetary magnetic-field topology is determined by the solar wind outflow and the rotation of the sun which during "quiet" conditions can be approximated by an Archimedian spiral as illustrated in Fig. 4. By examining solar proton data, we can generalize and separate the propagation of solar protons from the flare site to the Earth into two independent phases: 1) diffusion in the solar corona and 2) transport into the heliosphere along the interplanetary magnetic-field lines. Both phases are illustrated in Fig. 5. The coronal propagation distance is indicated in Fig. 5 by the heavy arc on the sun.

The maximum particle flux is assumed to occur at the solar flare site with a gradient extending in the corona from the flare site to other heliolongitudes. This gradient attenuates the maximum particle intensity as the angular distance from the flare site increases. There has been evidence for such a gradient since the early systematic analysis of spacecraft observations of solar particles.[18-22] Although observations suggest that the gradient varies between events, a decrease of a factor of 10 per rad is reasonable for estimating the solar particle flux at heliolongitudes away from the flare site. As the particles diffuse through the solar corona they are transported into the heliosphere along the interplanetary magnetic-field line.

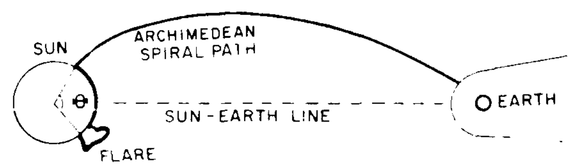

Fig. 5 Illustration of the propagation concept.

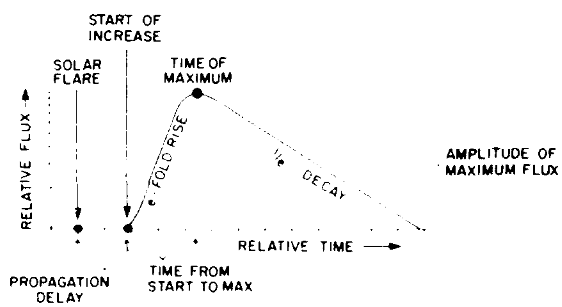

Fig. 6 General characteristics of solar proton events observed at 1 a.u.

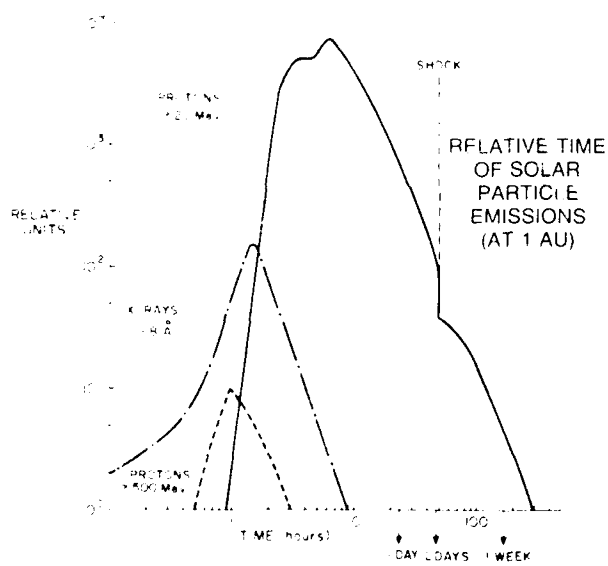

Fig. 3 Time scales of solar emissions arrival at 1 a.u.

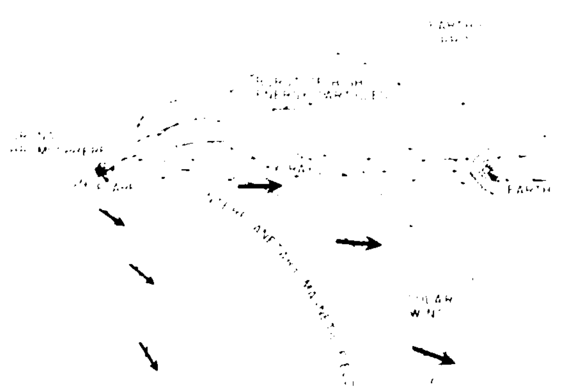

Fig. 4 Characteristics of the idealized structure of the interplanetary medium.

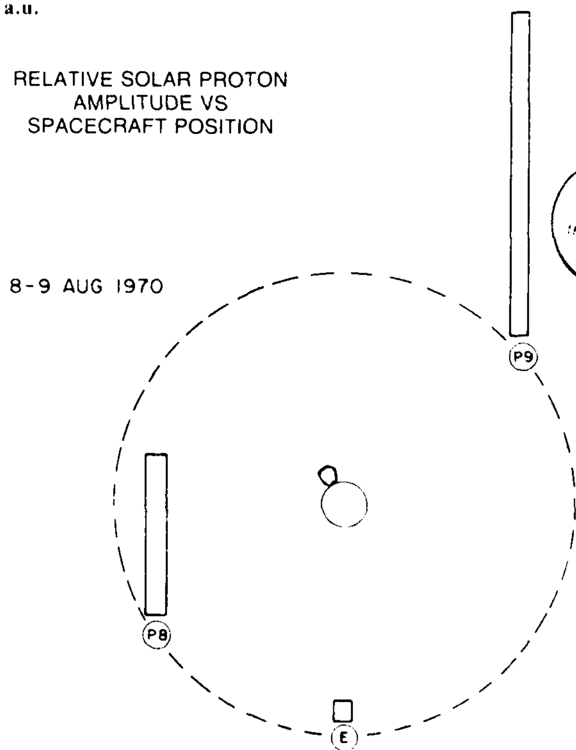

Fig. 7 Particle increases on August 8 and 9, 1970, at space probes and the Earth.

Table 1 Normalized elemental abundances of solar energetic particle events

		1 MeV[25,26]		1-20 MeV[27]		10 MeV[28]		6.7-15 MeV[29]	
		Energy	Range	Energy	Range	Energy	Range	Energy	Range
1	H	1.0		1.0		1.0		1.0	
2	He	2.2	E-2	1.5	E-2			1.5	E-2
3	Li			1.0	E-7	4.8	E-8	2.8	E-6
4	Be			1.5	E-7	6.0	E-9	1.4	E-7
5	B			1.5	E-7	1.2	E-8	1.4	E-7
6	C	1.6	E-4	1.2	E-4	9.6	E-5	1.3	E-4
7	N	3.8	E-5	2.8	E-5	2.7	E-5	3.7	E-5
8	O	3.2	E-4	2.2	E-4	2.2	E-4	2.8	E-4
9	F			4.3	E-7	1.0	E-8	1.4	E-7
10	Ne	5.1	E-5	3.5	E-5	3.1	E-5	3.6	E-5
11	Na	1.6	E-6	3.5	E-6	2.6	E-6	2.4	E-6
12	Mg	4.8	E-5	3.9	E-5	4.3	E-5	5.2	E-5
13	Al	3.5	E-6	3.5	E-6	3.1	E-6	3.3	E-6
14	Si	3.8	E-5	2.8	E-5	3.5	E-5	4.2	E-5
15	P	2.3	E-7	4.3	E-7	1.7	E-7	4.0	E-7
16	S	1.8	E-5	5.7	E-6	7.8	E-6	6.5	E-6
17	Cl	1.7	E-7			7.1	E-8		
18	Ar	3.9	E-6	8.7	E-7	7.3	E-7	4.6	E-6
19	K	1.2	E-7			1.0	E-7		
20	Ca	2.3	E-6	2.6	E-6	3.1	E-6	3.2	E-6
21	Sc					7.8	E-9		
22	Ti	1.0	E-7			1.2	E-7		
23	V					1.2	E-8		
24	Cr	5.7	E-7			5.0	E-7		
25	Mn	4.2	E-7			1.8	E-7		
26	Fe	4.1	E-5	3.3	E-5	3.4	E-5		
27	Co	1.0	E-7			4.8	E-7		
28	Ni	2.2	E-6			1.2	E-6		
29	Cu					1.4	E-8		
30	Zn					3.8	E-8		

Particle events at 1 a.u. exhibit the following characteristics: a delay from the solar flare time until the first particles are detected, a relatively rapid rise in intensity to a maximum value, and a slow decay to the background level. In general, particle events from the eastern hemisphere of the sun have slower rates of rise than events from flares west of central meridian. Although the shape of an event may be distorted by features in the interplanetary medium at the time of the solar particle event, or the particle flux may be considerably modified by multiple injections or interplanetary shocks, the general features of the solar proton time-intensity profile, shown in Fig. 6, are always recognizable. This profile is characteristic of the inner heliosphere; at distances beyond about 5 a.u. all solar particle events are diffusive in character. However, distinct solar flare particle increases have been observed by the most distant spacecraft, now out more than 40 a.u.

At times, major solar flares populate the entire inner heliosphere with particles, as illustrated in Fig. 7 where the vertical bars indicate the relative flux increase at each spacecraft. On August 8 and 9, 1970, particle increases on the Pioneer 8 and 9 space probes together with the small increase on the Earth-orbiting IMP 5 satellite were not associated with any solar activity on the visible hemisphere of the sun; however, active region 10882, which produced particle events on August 13 and 14, 1970, was on the invisible hemisphere of the sun about three days before east limb passage.[23] A flare source located approximately 40° behind the east limb is consistent with the large increase on August 8 observed by Pioneer 9, the smaller increase of flux observed on August 9 by Pioneer 8, and the even smaller increase observed at the Earth.

To summarize the "classical" or expected solar particle propagation characteristics, an observer who is connected via the interplanetary magnetic-field line to the heliographic location of the flaring region will generally observe the maximum possible particle intensity. An observer whose interplanetary magnetic-field connection is at some other heliocentric location would observe a flux that has been attenuated by propagation through the coronal gradient between the flare position and the foot point of the Archimedean spiral path from the sun to the detection position in space. The onset time of the particle event, the time of maximum intensity, the maximum (peak) particle flux, and the total fluence of the event are all functions of the location of the flare with respect to the observation location in space and the interplanetary conditions at the time of the flare.

Composition of Solar Particle Events

Solar energetic particles are assumed to be accelerated above solar active regions from the available coronal material during solar flare events. The acceleration site is apparently high in the solar corona; studies have concluded that the accelerated ions pass through less than 30 mg cm^{-2} of material between the acceleration site and the observation site in the interplanetary medium. Observations show variations in the ion abundances with the hydrogen-to-helium ratios being the most variable. The elemental abundance ratios seem to have a slight variation according to the energy of the measurement, and small solar cosmic-ray events have the greatest variability in elemental composition. (See Refs. 24 and 25 for recent views on the elemental abundances in solar particle events.) When elemental abundances observed in large solar energetic particle events are plotted vs the first ionization potential of each element, a depletion of the solar particle abundances is found for elements with first ionization potential above 10 eV. When elemental abundances are ordered by the first ionization potential, elements with both high and low first ionization potential are consistent with known coronal abundances, indicating that these ions were accelerated out of normal coronal material.

The same principles involved for organizing proton (ions with $Z = 1$) data also apply to heavy ions since the same principles of coronal and interplanetary propagation should apply to all ions independent of mass or atomic charge. Unfortunately, most of the solar particle data sets currently available are for protons. In order to estimate the probable heavy-ion fluence from the proton fluence, we have derived tables (see Table 1) of solar particle event element abundance ratios normalized to hydrogen based on comprehensive spacecraft studies.[26-29]

Historical Summary of Solar Particle Event Detection Techniques

A number of different detection techniques have been used to detect solar cosmic-ray events, and Fig. 8 illustrates the evolution of detection energy thresholds and detector techniques. The thickness of the lines indicates the relative number of each type of detector in use. The differences in shading in the ionospheric section indicate changes in detection technique. The first instances where the sun was unambiguously identified as the source of particles detected at the Earth were on February 28 and March 7, 1942. The measurements of the solar activity (observed as interference in detection and surveillance equipment) were shrouded in secrecy by the antagonists of the Second World War.[30] It was not until July 25, 1946, and November 19, 1949, that similar events occurred and the explanation of solar flare accelerated particles being detected on the Earth was given respectable scientific credence.[31,32] The initial observations of "solar cosmic rays" relied on measurements of secondary particles generated at the "top" of the Earth's atmosphere. The original ionization chambers and counter telescopes are now classed as muon detectors; these detectors respond to high-energy (>4 GeV) protons interacting at the "top" of the atmosphere. In the 1950's, development of the cosmic-ray neutron monitor[33] lowered the detection threshold to >450 MeV protons interacting at the "top" of the atmosphere. A number of these neutron monitors were deployed for the International Geophysical Year (IGY), and many neutron monitors are still operating although the design has evolved with the development of the so-called "super" neutron monitor.[34] Concurrently, with advances in nuclear physics, more sensitive instruments were developed that could directly measure the incident particles. These detectors were initially carried by balloons to get above as much of the Earth's atmospheric shield as possible; later these detectors were adapted for the initial man-made Earth-orbiting satellites.

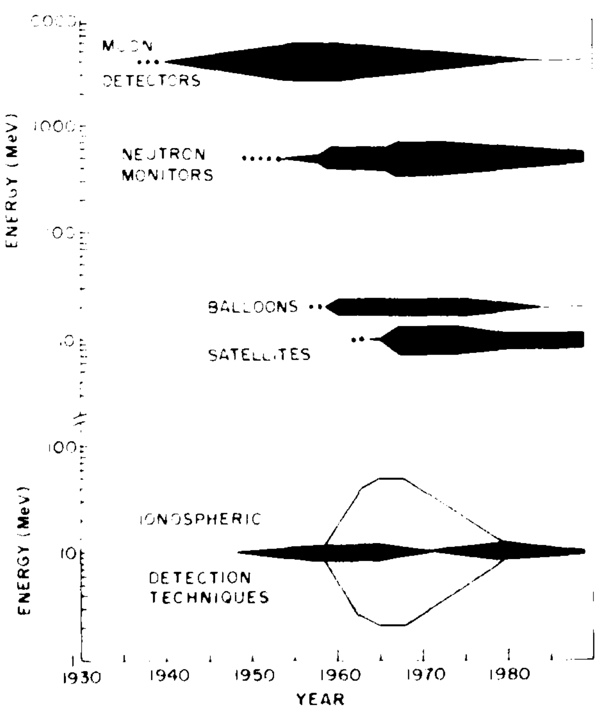

Fig. 8 Conceptual history of the detection thresholds of solar cosmic-ray events.

While cosmic-ray researchers were developing their instrumentation, high-frequency communication engineers, particularly those involved in the propagation of electromagnetic signals in the polar regions, noted interference that seemed to be associated with solar activity. It is now known that charged particles interacting with the Earth's ionosphere enhance the ionization and change the electromagnetic propagation characteristics of the medium. In the late 1950's, the development of the riometer[35] (for radio ionosphere opacity meter) proved to be very sensitive to particle deposition in the ionosphere directly above the instrument. Even though the riometer could not uniquely distinguish the type of particle, its sensitivity was equivalent to the early satellite instruments. Most of the solar particle flux and fluence data available from the 19th solar cycle were derived from riometer measurements in the Earth's polar regions. Even now the ionosphere can still be used as a very sensitive (but nonlinear) particle detection medium, since very low frequency phase and amplitude changes along transpolar propagation paths have the same approximate detection thresholds as particle detectors on spacecraft.

Solar Proton Events: 1955–1986

Existing Data Base

As can be seen from inspection of Fig. 8, there are Earth-based measurements of solar flare generated particles since 1942. However, the indirect detection techniques did not stabilize until approximately 1958, and the spacecraft measurements were not really systematic until about 1965. Based on contemporary knowledge, it is possible to interpret the ionospheric-sensed data to form a useful data base extending back until about 1955. Inclusion of all of the available ground-based and satellite-sensed measurements form a data base extending over three solar cycles. The data base for solar cycle 19 is primarily derived from ionospheric data supplemented with limited spacecraft data in the early 1960's. The data base for solar cycle 20 is derived from Earth-orbiting satellite measurements of solar particle events plus simultaneous ionospheric measurements that allow a cross calibration of the detection techniques. Finally, the data base for solar cycle 21 is derived primarily from very sensitive spacecraft instruments (so sensitive, in fact, that they "saturate" in large events), with only a minor contribution from ionospheric data since many of the polar ionospheric monitoring stations had closed. There have been a number of attempts to assemble available solar proton data into catalogs.[36-40] The National Oceanic and Atmospheric Administration/U.S. Air Force Space Environment Services Center in Boulder, Colorado, maintains a current list of solar proton events; see Ref. 41.

Until a reliable direct-measurement (satellite sensed) solar particle data base was available, there were always questions as to the accuracy of the early data bases and the magnitude of contamination by local magnetospheric effects. It is not possible to assemble a completely homogeneous list of solar proton events detected over the last three solar cycles, primarily because of the different measurement techniques used. The most homogeneous data set available that has been derived from a standard observational technique are the "ground-level events" (sometimes called relativistic solar proton events) detected by neutron monitors, since the sensitivity of this instrument has been essentially unchanged since its inception in 1953. During the 19th solar cycle, some small ground-level events may not have been identified because of a sparsity of detectors. Since the early 1960's, a denser net of instruments has been installed, particularly in the Earth's polar regions, and events with increases of only a few percent have been

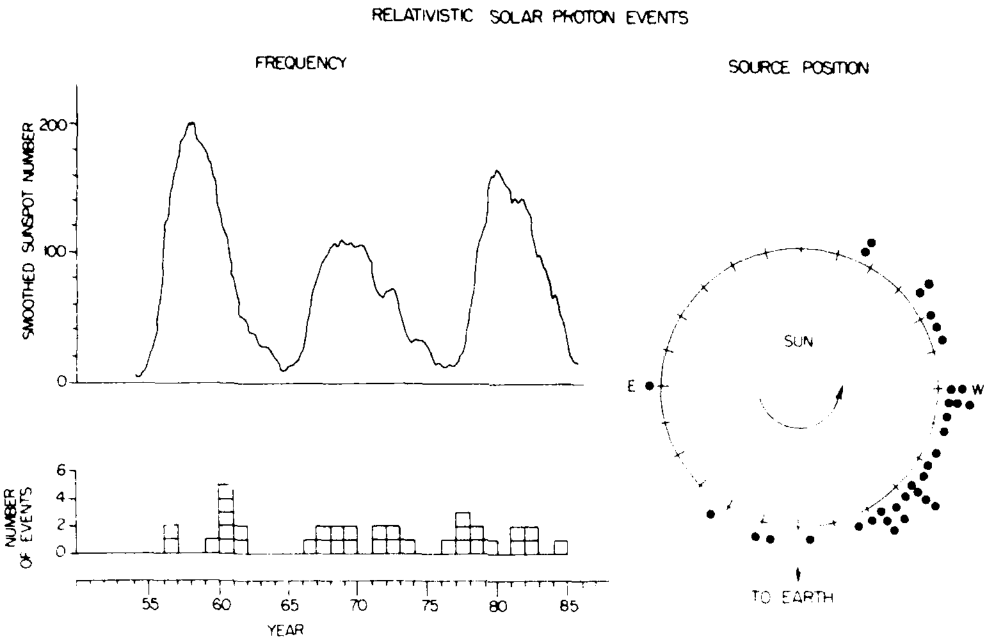

Fig. 9 High-energy solar proton events for three solar cycles.

readily identified since 1966. Figure 9 shows the distribution of these relativistic solar proton events over the past three solar cycles; the top part of the figure shows the smoothed sunspot number; the bottom part of this figure shows the number of high-energy solar particle events (GLE events) each year; and the right part of the figure shows the location of the source solar flare on the sun. An examination of Fig. 9 (at least to our prejudiced eye) does not indicate any outstanding trends other than the general association with solar activity.

It is possible that the terms "solar particle flux" and "solar particle fluence" may be confused. Particle physicists usually refer to the peak flux observed in a specific channel of a solar particle detector. This can be either an integral flux above a specified energy level, in units of particles (cm^{-2}-s^{-1}-sr^{-1}) or a differential measurement that specifies the flux at a specific energy in units of particles (cm^{-2}-s^{-1}-sr^{-1}-MeV^{-1}). Individual events are usually compared using identical channels. Peak flux is usually used to describe solar particle events. Fluence is the total number of particles above a selected energy that are experienced throughout an entire event. Fluence may be given in either directional units of particles (cm^{-2}-sr^{-1}) or omnidirectional units of particles (cm^{-2}). The fluence is generally of concern for the total radiation exposure. During an episode of activity, there may be a number of individual solar particle events that contribute to the total radiation exposure. Under these circumstances, instead of trying to derive the fluence per solar flare injection, which is extremely difficult, a pragmatic solution is to obtain the fluence per episode of activity.

In an attempt to investigate the solar cycle effects on solar particle events, we have assembled a list of solar proton events that is as homogeneous as possible. Our criterion for this event list was to identify all >10 MeV solar proton events having a minimum flux of 10 protons (cm^2-s^1-sr^{-1}); a criterion that could be applied uniformly over three solar cycles. Spacecraft-measured proton fluxes were used whenever they were available. For the pre-spacecraft era or when spacecraft data were not available, an equivalent proton-induced polar cap absorption event was used. A practical "rule of thumb" useful for converting sunlit polar cap riometer absorption to proton flux is $J = 10A^2$, where J is the flux of protons with energy >10 MeV in units of (cm^2-s-sr)$^{-1}$ and A is the 30-MHz polar cap riometer absorption in decibels. Thus, 10 protons (cm^2-s-sr)$^{-1}$ with energies >10 MeV are approximately equivalent to a 1-dB polar cap absorption event. Our primary data sources were Refs. 39 and 40, and data assembled by Shea and Smart.[42,43] Measurements from the synchronous orbiting GOES spacecraft[41] were used for the years 1976-1986.

Table 2 lists the number of discrete solar proton events with a flux >10 particles (cm^2-s-sr)$^{-1}$ as a function of month for the past three solar cycles (1955-1986). The yearly sums are shown in the top portion of Fig. 10, and the yearly average sunspot numbers are shown in the bottom portion of this figure. Table 2 shows that significant solar proton events occur in episodes with a large variance in the distribution. There can be relatively long periods between significant events during the sunspot solar maximum; conversely, significant solar proton events, including ground-level events, have occurred during solar minimum. Of the 201 significant particle events during the past three solar cycles, 34 of them have been ground-level events detected by neutron monitors indicative of solar protons with energies greater than 450 MeV.

Data Artifacts

A careful examination of the data-acquisition techniques reveals a number of artifacts that may obscure any long-term trends. The identification of solar proton events by interpreting ionospheric data is affected by at least two pronounced seasonal effects. The riometer is most sensitive to the sunlit polar ionosphere (its nighttime response is about one order of magnitude less sensitive), and since most polar ionosphere observing sites are in the northern hemisphere (particularly during the 19th solar cycle), there is a distinct northern hemisphere bias in the ionospheric data with more events reported in the northern hemisphere summer than the northern hemisphere winter. The ionosphere also has a strong response to geomagnetic activity, which has a statistically significant peak during the equinox. These two effects combine to give a very nonuniform temporal distribution of the data assembly, particularly during the 19th solar cycle as illustrated in Fig 11. The magnitude of the seasonal bias is not generally appreciated and has crept into data sets considered quite reliable. Satellite-sensed data assemblies[44] still show a seasonal bias at the lowest flux threshold as shown in the top part of Fig. 12, which displays the number of > 10 MeV solar proton events with a flux greater than 1 particle (cm^2-s-sr)$^{-1}$. In this case, we believe that the apparent maximum around the equinox is real,

Table 2 $E > 10$ MeV solar proton events with flux $> 10\ (cm^2\text{-}s\text{-}sr)^{-1}$

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1955	1	.	.	.	.	.	.	.	.	.	.	.	1
1956	.	1	1	.	.	.	.	.	1	.	1	.	4
1957	1	.	.	2	1	1	2	3	4	1	1	.	16
1958	.	1	2	1	.	.	2	4	1	.	.	.	11
1959	.	1	.	.	1	1	3	1	.	.	.	.	7
1960	1	.	1	4	3	.	.	.	2	.	3	.	14
1961	.	.		.	.	.	4	.	3	.	1	.	8
1962	.	1	.	.	.	.	.	.	.	.	.	.	1
1963	.	1	.	.	.	.	.	.	2	.	.	.	3
1964	.	.	.	.	.	.	.	.	.	.	.	.	0
1965	.	1	.	.	.		.	.	.	.	.	.	1
1966		.	1	.	.	.	1	1	2	.	.	.	5
1967	1	1	1	.	2	1	.	.	.	.	.	1	7
1968	.	.	.	.	.	1	2	.	2	2	3	2	12
1969	1	4	1	1	1	1	.	.	1	.	2	1	13
1970	.	1	2	.	1	1	1	1	.	.	1	.	8
1971	1	.	.	1	1	.	.	.	1	.	.	1	5
1972	1	.	.	1	1	1	1	3	.	1	.	.	9
1973	.	.	.	1	.	.	.	.	1	.	.	.	2
1974	.	.	.	.	.	.	4	.	3	.	1	.	8
1975	.	.	.	.	.	.	.	2	.	.	.	.	2
1976	.	.	.		1	.	.	.	.	.	.	.	1
1977	.	.	.	.	.	.	.	.	3	.	1	.	4
1978	.	1	.	5	1	2	1	.	1	.	1	.	12
1979	.	1	.	1		1	1	1	1	.	1	.	7
1980	.	1	.	.	.	.	1	.	.	.	.	.	2
1981	.	.	1	2	2	.	2	1	.	2	.	1	11
1982	1	.	.	.	.	2	2	.	1	.	2	4	12
1983	.	1	.	.	.	.	1	.	.	.	.	.	2
1984	.	2	2	1	2		.	.	.	.	.	.	7
1985	1	.	.	1	.		1	.	.	.	.	.	3
1986	.	2	.	.	1	.	.	.	.	.	.	.	3
1987	.	.	.	.	.	.	.	.	.	.	.	.	0
	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
	9	20	12	21	18	12	29	17	29	6	18	10	201

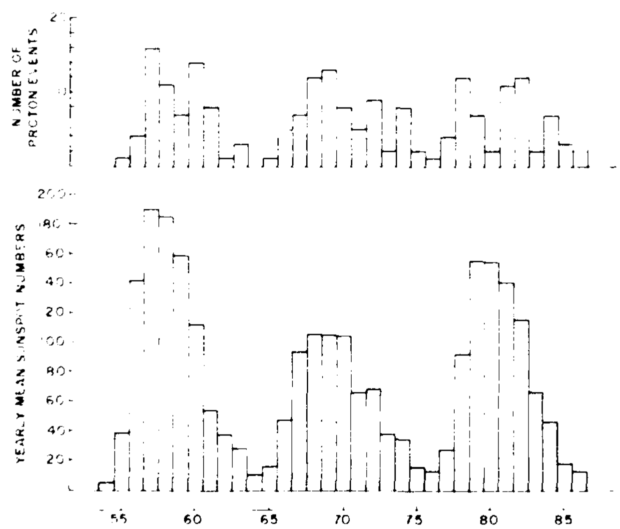

Fig. 10 Discrete solar proton events per year (top) and the yearly sunspot number (bottom)

possibly reflecting interplanetary acceleration processes. Another data artifact exists in the 19th solar cycle proton flux and fluence data as a result of exponential forms used to model the data[17,45-49] which introduces apparent systematic behavior into some events, particularly the events derived from interpretation of ionospheric measurements. When the extramagnetospheric satellite-sensed solar proton event data for solar cycle 20 (such as NSSDC data set 69-053A-07C[50]) are summed over event intervals, similar systematic patterns are not found.

Solar Proton Events and the Solar Cycle

In trying to determine solar cycle similarities or differences in solar proton events from the past three solar cycles, we used the monthly mean sunspot number[51] as our major ordering parameter We used month of the minimum in the smoothed sunspot number to identify the change from one solar cycle to the next, since the monthly mean numbers have a wide variance during solar minimum. The top portion of Fig. 13 shows the number of solar proton events that occurred each 12-month period after sunspot minimum for the past three solar cycles; the 12-month mean sunspot number of the same period is shown in the bottom of the figure. A summary of the number of events for each solar cycle is given in Table 3. The three histograms in the top part of Fig. 13 are all different, and beyond the obvious fact that there are more solar proton events during solar activity maximum than at solar minimum, we cannot discern any repeatable pattern other than the general association with solar activity. The only constancy is that there is an average of six significant solar proton events per year independent of the length of each cycle. Using solar minimum as our fiducial mark, we have added the values for each cycle; the results are displayed in Fig. 14. The data are organized in 12-month periods beginning with the month after statistically smooth sunspot minimum. From Fig. 14 it appears that the majority of solar proton events will occur from the second through eighth years after sunspot minimum. The apparent peak in the number of proton events in the 10th year after sunspot minimum is an artifact resulting from the episodes of activity in the 10th year of solar cycle 20, which was 14 months longer than the other two cycles.

Episodes of Activity

In compiling the list of significant solar proton events, we tried to identify each event with a solar flare on the sun. In

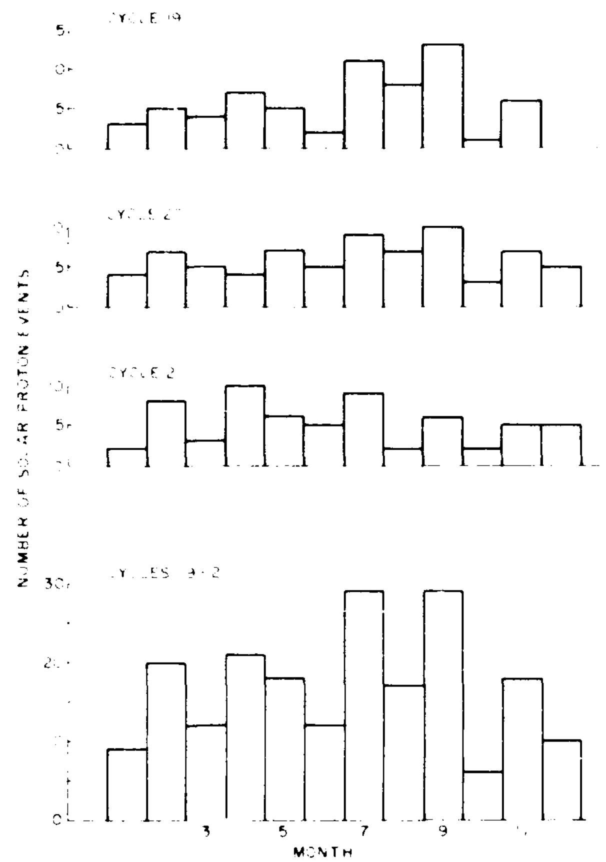

Fig. 11 Nonuniform temporal distribution of proton events for three solar cycles.

many cases, there were multiple flares on the sun, all of which may have released particles associated with the aggregate particle event observed at the Earth. There were two types of sequences of activity, the most common being multiple particle events associated with multiple flares from the same active region. The other type of activity sequence occurs when different regions on the sun each produce copious solar particles. We have calculated the number of discrete solar proton producing regions associated with proton events detected at the Earth for each of the last three solar cycles (i.e., multiple events from the same region contributed to only one episode). These results, listed in Table 3, show that for each of the last three solar cycles at least 17% of the significant solar proton events observed at the Earth are from solar regions that produce at least two or more discrete proton events.

Statistical Limitations

The small number of events during the past 33 years severely limits statistical analyses. Typical spacecraft engineering procedures ask for reliability analyses with 90% confidence factors; Table 2 clearly shows that there is not enough data to satisfy such a requirement. The practice of dividing the available data into solar cycle groups further limits the statistics, and the results are open to a variety of interpretations that cannot be squelched by application of statistical techniques.

Despite its limitations, this data base or a portion of it has been analyzed in a number of different ways to develop statistics and models of solar particle event frequency, magnitude, and fluence.[45,52-56] The 1975 NASA model[55] is still in use today and is the contemporary standard against which other work is compared. In the past few years, this model has been attacked as being too limited and not truly representative of

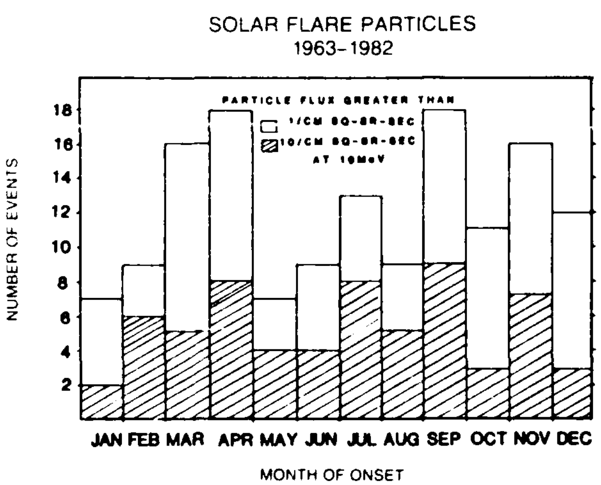

Fig. 12 Illustration of the seasonal bias in solar proton data.

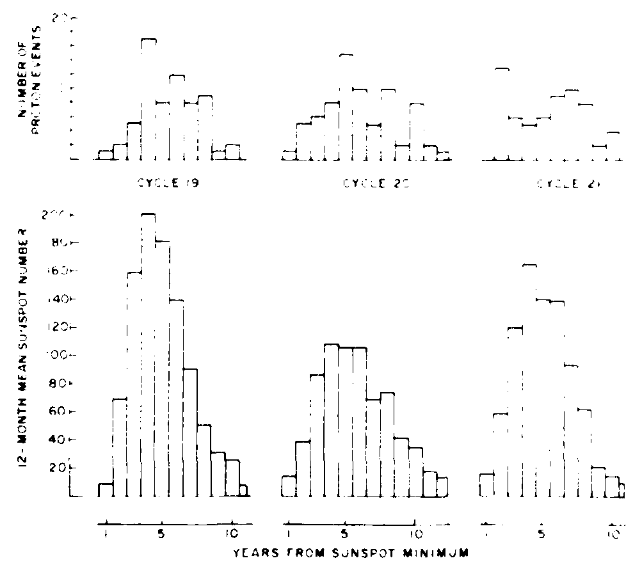

Fig. 13 Significant discrete solar proton events for each 12-month period after solar minimum.

Table 3 Solar proton events for solar cycles 19-21

Cycle	Start[a]	End	No. of months in cycle	No. of discrete proton events	No. of discrete producing regions	Solar cycle integrated solar proton fluence >10 MeV	Solar cycle integrated solar proton fluence >30 MeV
19	May 1954	Oct. 1964	126	65	47	6.7×10^{10}	1.1×10^{10}
20	Nov. 1964	June 1976	140	73	56	2.5×10^{10}	7.0×10^{9}
21	July 1976	Sept. 1986	123	63	52	1.8×10^{10}	6.1×10^{9}

[a]The start of each solar cycle was selected as the month after the minimum in the smoothed sunspot number.

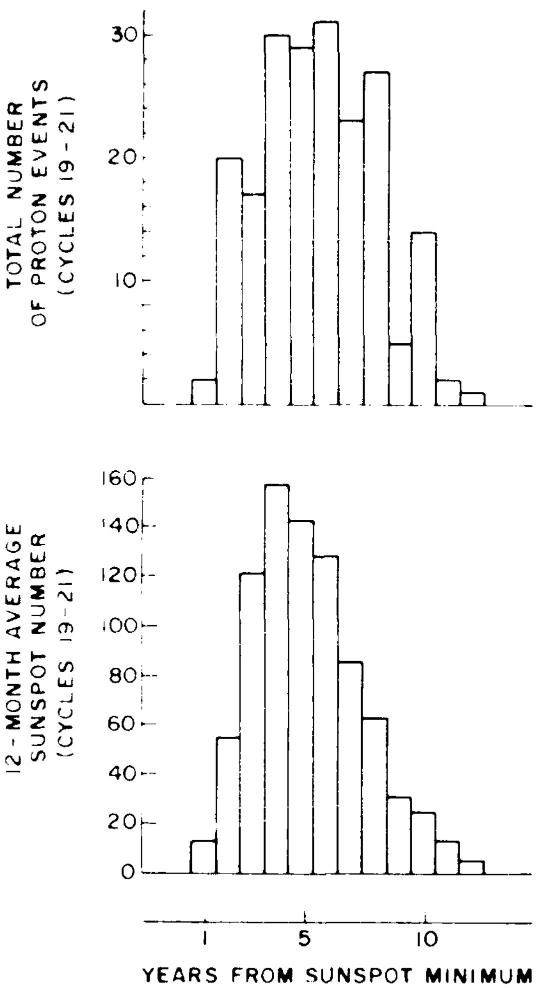

Fig. 14 Summation of significant discrete solar proton events for cycles 19-21.

what can occur. Curiously, there are two attacks: 1) that its predictions are too high because very large fluence events were not observed by Earth-orbiting satellites during the 21st solar cycle,[illegible] and 2) that it does not properly include the possibility that very large fluence events could, and historically, have occurred.[illegible]

Worst-Case Models

In developing worst-case models, the very large or very energetic particle events are employed instead of the common events. It is our opinion that the very large particle events may be expected to have "normal" elemental abundance ratios. For this paper, we will suggest two solar particle events for use as extreme-case models. The first type is a "classical" very energetic solar particle event having a discrete injection of flare-accelerated particles along the idealized interplanetary propagation path from the sun to the Earth. For this example, we will use the February 23, 1956, solar particle event. The second type of event is the injection of a large population of solar particles that is reaccelerated by interplanetary phenomena before detection at the Earth. For this example, we shall use the August 4, 1972, solar particle event.

The fluence data base contains a detection technique artifact that essentially cannot be removed. The tremendous advances in detector technology are such that satellite sensors now routinely detect events that were far below the detection threshold even 15 years ago. The 19th solar cycle is deficient in "small event" identification; however, it contains the largest solar particle events and event fluences. The 20th solar cycle was the first solar activity cycle that was systematically observed using space-borne instrumentation. The data base for the 21st solar cycle contains many small events that have been well observed by contemporary sensitive particle detectors; however, the event integrated fluence of these "small events" is very small compared to the major events. The analysis by Feynman et al.[illegible] concludes that all of the fluence data for the three solar cycles combine to form a continuous log-normal distribution that is representative of solar particle history. In contrast, other researchers,[illegible] using smaller data sets, found a smaller distribution function for which the very large events are not part of the "expected" log-normal distribution, and so they calculated independently the probability of a very large event.

Table 3 presents the solar cycle summed fluences with energies greater than 10 and 30 MeV. These can be interpreted as showing a systematic downward trend; however, this trend does not match the maximum sunspot number for the respective cycles. Furthermore, the difference between cycle 20 and 21 integrated fluences can be interpreted as the occurrence (or nonoccurrence near the Earth) of one very large solar particle episode.

Organization of the Solar Particle Data Base with Other Parameters

Obviously, solar proton event data can be organized against many solar parameters such as sunspot number, 10-cm radio emission, solar flares, solar x-rays, and so forth. There is no reason, at this time, to select any particular parameter over any other. We have compared the number of significant solar proton events with solar flares of importance 1 or greater.‡ However, even for solar flare data many caveats must be appended because during the past three solar cycles there have been drastic changes in observing sites, reporting criteria, and data grouping specifications. The solar flare data shown in Fig. 15 were derived from NGDC01.[illegible] Although there are general trends between proton events and solar activity, as identified by either the sunspot number or solar flares, there is no obvious linear relationship. However, the "variance" in the number of significant proton events per year is consistent with the range expected from a binomial distribution or other mathematical techniques appropriate for the statistics of small numbers.

The February 23, 1956, solar particle event is the classic example of a discrete high-energy particle injection from the sun at a "favorable" propagation position with respect to the Earth. The solar flare that was the particle source occurred at 0334 Universal Time (UT), sometimes referred to as Greenwich Mean Time, at heliographic coordinates N23, W80. Protons with energies greater than 16 GeV arrived at the Earth at 0345 (± 1 min). The energy content of this solar particle event has not been duplicated by Earth-based measurements in the three solar cycles since the event occurred. Since this event was prior to the IGY and before the "space" era, ground-based measurements were fragmentary, and some of the early analyses are deficient when viewed with modern knowledge. The high-energy flux estimate[45] was ~ 150 particles $(cm^2\text{-}s\text{-}sr)^{-1}$ at energies > 450 MeV. This was not an extremely large fluence event at energies of about 30 MeV.[45,47,52] Interplanetary conditions were relatively "quiet" when this event occurred, and the particle flux decayed in a classical manner. After about 12 h, the very energetic particles had diffused beyond the Earth, and the remaining particle flux could be treated as an ordinary particle event. However, during the initial 12 h, there was certainly a large, very energetic particle ra-

‡Solar flares are classified by the area of the flare on a scale of 0 to 4. The smallest sub-flares (those with a corrected area less than 2.06 square deg) are of importance 0 whereas extremely large flares (those with corrected areas greater than 24.7 square deg are of importance 4.

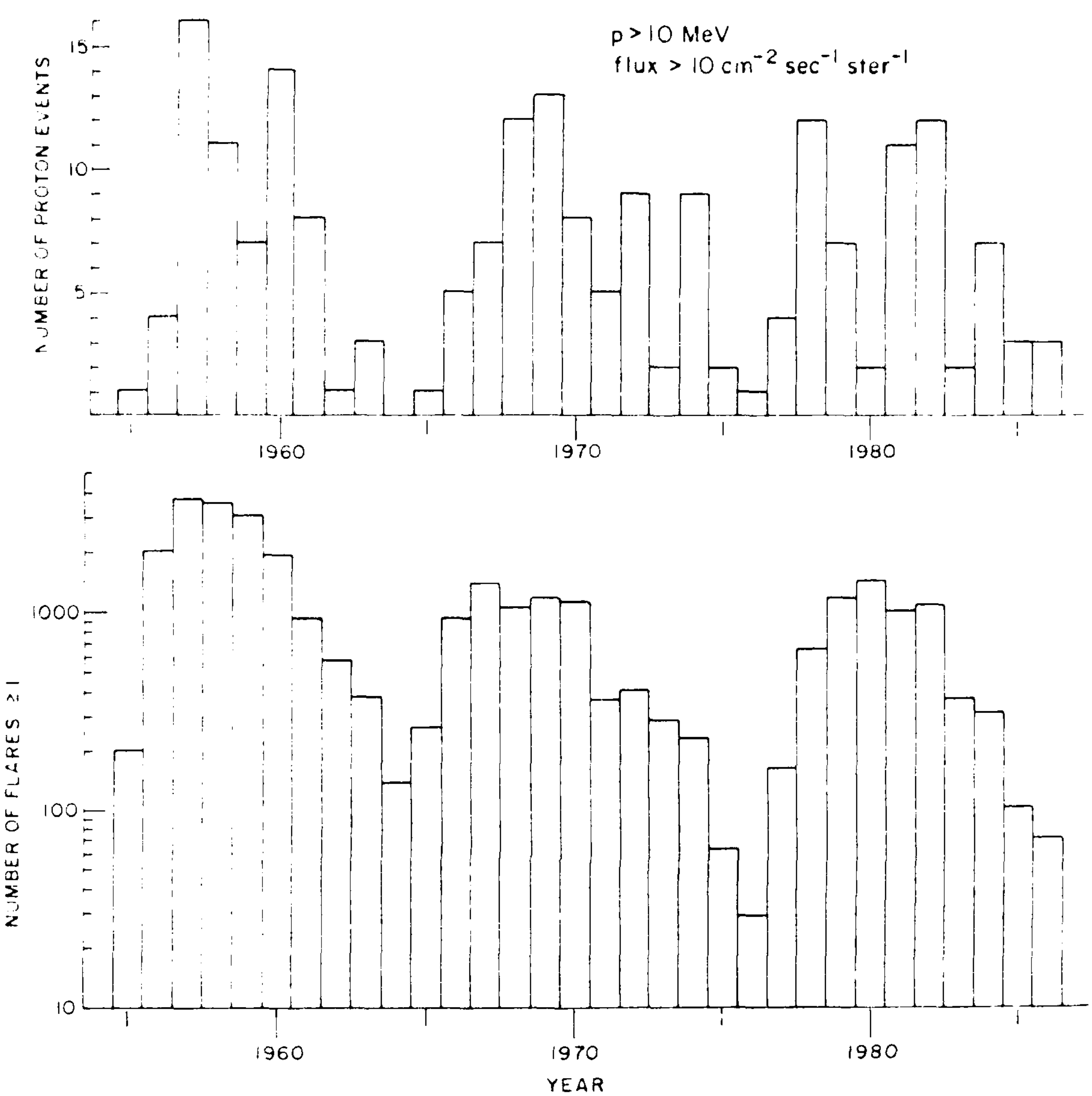

Fig. 15 Yearly number of solar proton events (top) and solar flares with importance ≥ 1.

diation exposure that would affect vulnerable devices and constitute a radiation hazard.

The solar particle event most often used as a "worst-case model" is the August 1972 episode of solar activity because Earth-orbiting spacecraft measurements of the particle flux and fluence exist. The solar active region was located at eastern heliographic longitudes; from the aspect of the Earth this was an eastern hemisphere event sequence. During this time, the Pioneer 9 spacecraft was at 0.77 a.u., 46° east of the sun-Earth line; from the aspect of the Pioneer 9 spacecraft, this was a western hemisphere event sequence. The initial particles that were observed were generated by a solar flare on August 2 at 0316 UT at a heliographic longitude 34° east of the sun-Earth line. The major particle event that was observed at the Earth on August 4 was generated by a solar flare at 0620 UT, 9° east of the sun-Earth line. The solar proton time-intensity history of early August 1972 is shown in Fig. 16. The Pioneer 9 data are for $E > 14$ MeV protons indicated by the heavy line. The Earth-orbiting IMP spacecraft data from protons with energies > 10 and > 30 MeV are indicated by the thin lines. Beginning with the solar flares from the same active region on August 2 until August 4, the particle flux observed by the Pioneer 9 spacecraft was larger than the flux observed at the Earth, as would be expected from coronal propagation and gradients. In contrast, however, on August 4 a larger flux is observed at the Earth than at the Pioneer 9 spacecraft.

It is our opinion that the August 4, 1972, solar particle flux profile observed at the Earth reflects a sequence of unique and unusual occurrences: the result of a large injection of solar particles into a region of space where the converging interplanetary shock structures reaccelerated what was a substantial solar particle population into an extraordinary solar particle population. (See Lee[58,59] for a more detailed discussion of shock acceleration.) Early on August 4, just prior to the flare, two geomagnetic sudden commencements were recorded at the Earth, indicative of the passage of solar-generated shock waves from flares in the solar active region that produced the major events. (The shock structures generated by the August 2 solar flares had already propagated beyond Pioneer 9 on August 4 when the major solar particle injection occurred.) When the flare of August 4 occurred at 0620 UT, the initial interplanetary shocks had just passed the Earth, leaving the Earth enveloped between the first shock ensemble and the much more powerful shock generated by the August 4 flare. While the Earth was enveloped between these two powerful converging shocks, the flux observed at the Earth was higher than that observed by Pioneer 9. The time period when the Earth was between the converging powerful

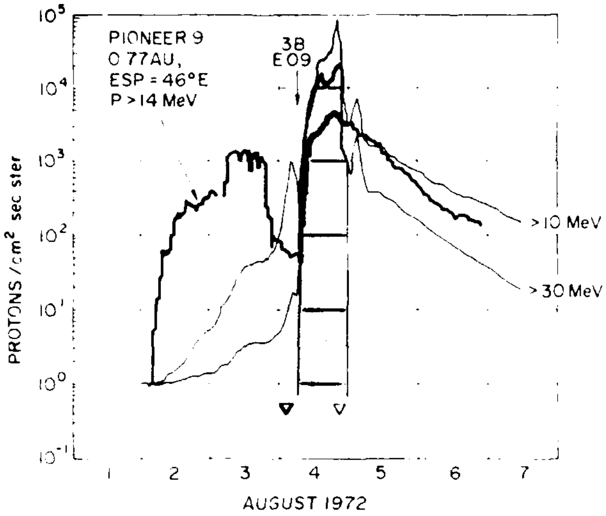

Fig. 16 Solar proton time-intensity profile observed for the August 1972 sequence of events.

interplanetary shocks is the only time when there is anything extraordinary about the observed particle flux. During this time, the Earth-observed particle flux was unusually high and had an extraordinarily hard spectrum. This time period, from about 06 UT to about 24 UT on August 4, is illustrated by the shaded portion of Fig. 16. After the converging interplanetary shock structure had passed the Earth, the Earth-observed time-intensity profiles resumed a classical appearance and match very well the results expected from application of proton prediction models such as those of Smart and Shea[60,61] These observations also suggest that these unusually large flux events can be limited in time and spatial extent.

In using the August 4, 1972, event to study major particle fluxes and worst-case scenarios, the question often asked is "Should an adjustment be made from the observed flux and fluence to a worst-case model by invoking coronal gradients?" as discussed previously in this paper. (The argument for doing this is that the solar flare did not occur at the most favorable propagation location for measurements at the Earth, and perhaps if this flare had been on the western hemisphere of the sun at a heliographic longitude of about 60° an even larger flux would have been observed at the Earth). We argue against making such an adjustment for the August 4, 1972, fluxes observed at the Earth and suggest that this is an example of interplanetary acceleration modifying the "initial injected" population of solar particles. A comparison with the particle flux measured by the Pioneer 9 spacecraft definitely does not support the "flux adjustment" hypothesis. The Pioneer 9 data on August 4 have been viewed with some skepticism precisely because the flux measured on Pioneer 9 is not what would be expected from the relative positions of the two measurement locations with respect to the flare on August 4. However, the Pioneer data are considered valid for scientific analysis before the August 1972 events and are again considered proper for scientific analyses after the August 1972 events. We suggest that the Pioneer 9 data are also valid during the August 1972 events. Thus, the "worst case" may well be what was actually measured at the Earth. To support this argument further, we note that Lingenfelter and Hudson[62] have argued that the analysis of returned lunar samples and cosmogenic isotopes indicates that events from our sun with fluence greater than 10^{10} protons (cm^{-2}) with energies >10 MeV are very rare. In addition, Goswami et al.[63] found that the mean flux values for the last three solar cycles agreed fairly well with the value deduced from solar flare proton and alpha particle induced radioactivity in lunar samples.

There was at least one other period during the past three solar cycles when the particle flux from a sequence of activity

Table 4 Comparison of the first 27 months of solar cycles 21 and 22

	Cycle 21	Cycle 22
Proton events	10	9
x-ray events (x-level)	19	13
Smoothed sunspot number[a]	64	84

[a] For month 20 after solar minimum.

was similar to that of August 1972. In July 1959, a series of solar flares near the central meridian of the sun produced major geomagnetic effects with resulting large variations in the galactic cosmic-ray intensity as measured by neutron monitors that recorded several "Forbush" effects in addition to a small "flare-associated" relativistic solar particle increase. These observations were very similar to neutron monitor observations in August 1972. We believe tha if satellite measurements had been available in July 1959, the fluence from this activity episode would have been equal to or greater than the fluence observed in August 1972. In fact, the fluence deduced for the July 1959 solar activity episode exceeds the measured fluence observed for the August 1972 solar activity episode.[45,47,52]

It is our opinion that the extraordinary events, such as those that occurred in July 1959 and August 1972, are the result of a sequence of major flares, particle events, and solar-generated interplanetary shock structures which contribute to the unusually large effect. These events are outstanding examples. The fact that the Earth did not record such a flux during the 21st solar cycle does not mean that these type of events did not occur somewhere on the sun. Indeed, we wish to use an analogy from terrestrial weather. A hurricane or a typhoon is the result of an unusual sequence of events that are likely to occur only during a certain season. These storms come to public attention only when they strike populated areas. Likewise, extraordinary solar-initiated storms only come to our attention when they envelope our planet. Our sensor net in space is so sparse that we are not likely to find such events elsewhere.

Solar Particle Events in Solar Cycle 22

Two years of solar cycle 22 have passed and although the initial rise of the sunspot number was the most rapid to date, the rate of rise now appears to be slowing. The number of solar proton events observed at this stage of the solar cycle (applying our discrimination threshold of events with energies >10 particles (cm^{2}-s-sr)$^{-1}$ is within expectations. However, the first relativistic solar proton event of this cycle, comparable to February 23, 1956, July 7, 1966, or November 22, 1977, has not been detected at the Earth.¶ Recognizing that we are dealing with small numbers, the statistics for the first 27 months of this cycle compared with the 21st cycle are as shown in Table 4.

Solar maximum is expected around the first part of 1990. Perhaps some of the particle events that we think should have occurred by now will occur during solar maximum. Perhaps 1990 will be like 1980, with only two significant solar proton events at the Earth. At the present time, with the sunspot number up and the number of x-ray events down, it would be foolhardy to try to predict the number and/or magnitude of proton events for solar cycle 22. All of which goes to prove—there is always something new under the sun!

Concluding Remarks

This paper does not have a definitive incontestable conclusion. We have tried to present the solar particle data available from three solar cycles in an unbiased manner and point out the limitations, deficiencies, and pitfalls inherent in an analy-

¶The first ground-level event of the 22nd solar cycle occurred on August 16, 1989. The 5.5-year interval between the ground-level events of February 16, 1984, and August 16, 1989, is the longest time interval between ground-level events since routine monitoring began in 1953.

sis of this data base. The violence of the 19th solar cycle was not totally repeated in the 20th or the 21st solar cycle. There are certain characteristics of the observed proton event distribution found by all investigators: the distribution of events is described by log-normal statistics. The data base is limited, and episodes of activity dominate the occurrences of solar particle events. Probability distribution of expected occurrences can, have been, and will continue to be derived. It is not clear that there is a systematic solar cycle related behavior in the data. Such trends may be present; however, the nonuniformity of the data and the dominance of episodic sequences of activity obscure any obvious trend. The available models may be viewed as "conservative," such as the Feynman et al.[52] model based on an analysis of all available data, "average," such as the NASA model[55] based only on direct satellite observations, or "liberal," such as the Chenette[56] model based only on the most most recent solar cycle. Therefore, any judgments of the acceptability of a specific model should be based on the risk involved.

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